Higgs Boson Self-Coupling at High Energy $\gamma\gamma$ Collider

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Abstract

We analyzed the double production and the triple self-coupling of the standard model Higgs boson at future $\gamma\gamma$ collider energies, with the reactions $\gamma\gamma \to f\bar{f}HH$ $(f = b, t)$. We evaluated the total cross section for $f\bar{f}HH$ and calculated the total number of events considering the complete set of Feynman diagrams at tree-level and for different values of the triple coupling $\kappa\lambda_{HHH}$. We have also analyzed the sensitivity for the considered reaction and we show the results as 95% C.L. regions in the $\kappa - M_H$ plane for different values of the center of mass energy and different levels of background. The numerical computation was done for the energies which are expected to be available at a possible Future Linear $\gamma\gamma$ Collider with a center-of-mass energy $500 - 3000\ GeV$ and luminosities of 1 and $5\,ab^{-1}$. We found that the number of events for the process $\gamma\gamma \to t\bar{t}HH$, taking into account the decay products of both t and H, is small but enough to obtain information on the triple Higgs boson self-coupling in a independent way, complementing other studies on the triple vertex.

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I. INTRODUCTION

The Higgs boson [1] plays an important role in the Standard Model (SM) [2] because it is responsible for generating the masses of all the elementary particles (leptons, quarks, and gauge bosons). However, the Higgs-boson sector is the least tested in the SM, in particular the Higgs boson self-interaction.

The search for Higgs bosons is one of the principal missions of present and future high-energy colliders. The observation of this particle is of major importance for the present understanding of fundamental interactions. Indeed, in order to accommodate the well established electromagnetic and weak interaction phenomena, the existence of at least one isodoblete scalar field to generate fermion and weak gauge bosons masses is required. Despite repeated success in explaining the present data, the SM cannot be completely tested before this particle has been experimentally observed and its fundamental properties studied.

The triple and quartic Higgs boson couplings [3–5] λ and $\tilde{\lambda}$ are defined through the potential

$$V(\eta_H) = \frac{1}{2}M_H^2\eta_H^2 + \lambda v\eta_H^3 + \frac{1}{4}\tilde{\lambda}\eta_H^4, \tag{1}$$

where η_H is the physical Higgs field. In the SM, we obtain $M_H = \sqrt{2\lambda}v$ as the simple relationship between the Higgs boson mass M_H and the self-coupling λ where $v = 246\ GeV$ is the vacuum expectation value of the Higgs boson. The triple vertex of the Higgs field H is given by the coefficient $\lambda_{HHH} = \frac{3M_H^2}{M_Z^2}$. An accurate test of this relationship may reveal the extended nature of the Higgs sector. The measurement of the triple Higgs boson coupling is one of the most important goals of Higgs physics in a future e^+e^- linear collider experiment. This would provide the first direct information on the Higgs potential that is responsible for electroweak symmetry breaking.

The future e^+e^- linear collider can not only be designed to operate in e^+e^- collision mode, but can also be operated as a $\gamma\gamma$ collider. This is achieved by using Compton backscattered photons in the scattering of intense laser photons on the initial e^+e^- beams. The design of the photon linear collider and physics opportunities are described in references [6, 7] and the possibility of measuring the HHH coupling is discussed in Refs. [4, 8, 9].

The triple Higgs boson self-coupling can be measured directly in pair-production of Higgs particles at hadron and high-energy e^+e^- linear colliders. Several mechanisms that are

sensitive to λ_{HHH} can be exploited for this task. Higgs pairs can be produced through double Higgs-strahlung of W or Z bosons [5, 10, 11], WW or ZZ fusion [4, 12–14] as well as through gluon-gluon fusion in pp collisions [15–17] and high-energy $\gamma\gamma$ fusion [4, 8] at photon colliders. In $\gamma\gamma$ collisions, double Higgs production is possible in several reactions at the tree level, and one process, $\gamma\gamma \to HH$, at the one-loop level:

$$\begin{aligned} WW \text{ double Higgs-fusion} &: \gamma\gamma \to WWHH, \\ \text{double Higgs-fermion} &: \gamma\gamma \to f\bar{f}HH, \\ \text{one-loop level} &: \gamma\gamma \to HH. \end{aligned} \tag{2}$$

As was studied in [4] the reaction $\gamma\gamma \to WWHH$ is free from any background except incorrect combinatorial of jets; for $M_H < 150\ GeV$, the main branching is four b-jets (with an invariant mass peak at M_H) plus jets from two additional W bosons, up to four, and/or a large missing energy. 8-jet events can be detected in total: For $M_H > 150\ GeV$, the signature includes up to twelve quark jets with the invariant mass peaking at M_W and M_H.

In the case of the process $\gamma\gamma \to f\bar{f}HH$, the important contribution happens when the considered fermion is a quark-top since the Higgs-fermion coupling is proportional to the fermion mass. For completeness, we have also calculated the contribution when the fermion is a b-quark. We have found that this last contribution is negligible ($\sigma \sim 10^{-6}\ fb$ for $M_H = 120\ GeV$ and $\kappa = 2$).

The study of the four-body processes with quark top t, $\gamma\gamma \to t\bar{t}HH$, in which the SM Higgs boson is radiated by a $t(\bar{t})$ quark at future $\gamma\gamma$ colliders [6, 7] with a c.m. energy in the range of 500 to 3000 GeV, as in the case of the DESY TeV Energy Superconducting Linear Accelerator (TESLA) machine [18], is necessary in order to know its impact on other processes and also to search for new relations that could have a clear signature of the Higgs boson production.

Another process with double Higgs production in $\gamma\gamma$ collisions is $\gamma\gamma \to HH$. This reaction proceeds at the one-loop level. Analytical results for the amplitude and a detailed numerical analysis were carried out in Refs. [8, 9].

The Higgs coupling with top quarks, the largest coupling in the SM, is directly accessible in the process where the Higgs boson is radiated off top quarks $\gamma\gamma \to t\bar{t}HH$. Consequently, this process can be used to probe the $t - \bar{t} - H$ Yukawa coupling directly. This process

also depends on the Higgs boson triple self-coupling, which could lead us to obtain the first non-trivial information on the Higgs potential. We are interested in finding regions that could allow the observation of the $t\bar{t}HH$ processes at the next generation of high energy $\gamma\gamma$ linear colliders. We consider the complete set of Feynman diagrams at tree-level (Fig. 1).

This paper is organized as follows: In Sec. II, we study the triple Higgs boson self-coupling through the processes $\gamma\gamma \to f\bar{f}HH$ at next generation linear $\gamma\gamma$ colliders. In Sec. III, we have considered the background for the process $\gamma\gamma \to t\bar{t}HH$ and we have studied their sensitivity to different values of the triple vertex. Finally, we summarize our results in Sec. IV.

II. CROSS-SECTION OF THE HIGGS BOSON DOUBLE PRODUCTION WITH TRIPLE SELF-COUPLING

In this section we present numerical results for $\gamma\gamma \to f\bar{f}HH$ $(f = b, t)$ with double Higgs boson production. Since the Higgs-fermion coupling is proportional to the fermion mass, we analyzed the t-quark case in more detail. We carried out the calculations using the framework of the Standard Model at next generation linear $\gamma\gamma$ colliders. For the initial photon we use the spectrum of backscattered photons for unpolarized beams as given in Ref. [19].

We use the CALCHEP [20] packages to check the different parts of the calculations of the matrix elements and cross-sections. These packages provide automatic computation of the cross-sections and distributions in the SM as well as their extensions at tree-level. We consider the high energy stage of a possible Next Linear $\gamma\gamma$ collider with $\sqrt{s} = 500 - 3000$ GeV and design luminosity 1 and $5\, ab^{-1}$.

A. Triple Higgs Boson Self-Coupling Via $\gamma\gamma \to f\bar{f}HH$ $(f = b, t)$

To illustrate our results of the sensitivity to the HHH triple Higgs boson self-coupling, we show the dependence of the cross-section on the center-of-mass energy of $\sqrt{s} = 500 - 3000$ GeV for $\gamma\gamma \to t\bar{t}HH$ in Fig. 2 for several values of the Higgs boson mass $M_H = 120, 140$ GeV. The variation of the cross-section for the modified triple couplings $\kappa\lambda_{HHH}$ is evaluated for some values of κ in the range $(-2, 2)$. The cross-section is sensitive to the value of the

triple couplings as well as to the Higgs boson mass. The sensitivity to λ_{HHH} increases with the collider energy, reaching a maximum at the end of the range considered: $\sqrt{s} \sim 3000$ GeV. As an indicator of the order of magnitude we present the Higgs boson number of events in Table 1 (of course we have to multiplicate for the corresponding Branching Ratios to obtain the observable number of events) for several Higgs boson masses, center-of-mass energy and κ values and for a luminosity of $1\,ab^{-1}$ and $5\,ab^{-1}$.

We also include a contours plot for the number of events of the studied processes in the $(\sqrt{s}, \kappa)$ plane with $M_H = 120, 140$ GeV and $5\,ab^{-1}$ in Figs. 3 and 4. These contours are obtained from Table 1.

Finally, for the $\gamma\gamma \to b\bar{b}HH$ process, the cross-section as a function of the center-of-mass energy $\sqrt{s}$ for $M_H = 120$ GeV and $\kappa = 2$ is negligible ($\sigma \sim 10^{-6} fb$). In these conditions we did not have the possibility to detect this process.

$\gamma\gamma \to t\bar{t}HH$	$M_H = 120$ GeV					$M_H = 140$ GeV				
κ / $\sqrt{s}(GeV)$	-2	-1	0	1	2	-2	-1	0	1	2
800	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)
1000	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)
1500	2 (10)	3 (15)	3 (15)	4 (20)	4 (20)	1 (5)	1 (5)	1 (5)	2 (10)	2 (10)
2000	5 (25)	5 (25)	5 (25)	6 (30)	7 (35)	3 (15)	3 (15)	3 (15)	3 (15)	4 (20)
2500	6 (30)	6 (30)	6 (30)	8 (40)	9 (45)	4 (20)	4 (20)	4 (20)	4 (20)	6 (30)
3000	7 (35)	7 (35)	7 (35)	8 (40)	10 (50)	5 (25)	5 (25)	5 (25)	5 (25)	7 (35)

Table 1. Total production of Higgs boson pairs in the SM for $\mathcal{L} = 1\,(5)\,ab^{-1}$ and $\kappa = -2, -1, 0, 1, 2$.

III. BACKGROUNDS AND SENSITIVITY

For the process that we are studying, $\gamma\gamma \to t\bar{t}HH$, we have considered the following background: $\gamma\gamma \to t\bar{t}ZH$ and $\gamma\gamma \to t\bar{t}ZZ$. If we consider a center-of-mass energy of $\sqrt{s} = 2000$ GeV of the parent e^+e^- and a Higgs boson mass of $M_H = 120$ GeV these process have total cross section of 0.006 fb and 0.004 fb respectively, while the signal process has

$0.006\ fb$. Considering that $Br(H \to b\bar{b}) \simeq 0.7$ and $Br(Z \to b\bar{b}) \simeq 0.15$ and after b-tagging one can expect the ratio to be $S/B \sim 4.5$. In Fig. 5 (a) we show the ratio

$$\frac{S}{B} = \frac{\sigma_{t\bar{t}HH} Br(H \to b\bar{b}) Br(H \to b\bar{b})}{\sigma_{t\bar{t}ZH} Br(H \to b\bar{b}) Br(Z \to b\bar{b}) + \sigma_{t\bar{t}ZZ} Br(Z \to b\bar{b}) Br(Z \to b\bar{b})}, \tag{3}$$

as a function of the center-of-mass energy $\sqrt{s}$ and different values of the Higgs boson mass. We also consider the separate contributions of the $t\bar{t}HZ$ and $t\bar{t}ZZ$ backgrounds in Fig. 5 (b).

We should note that the b-tagging would remove the possible background from W bosons due to a small branching ratio of $W \to cs$ and then we neglect the background from W bosons that come from the $\gamma\gamma \to b\bar{b}W^+W^-$ process.

In order to quantify the sensitivity of the considered reaction to different values of κ we use the statistical sensitivity, S_{stat}, which is defined as [21]:

$$S_{stat} \equiv \frac{N(\kappa) - N_{SM}}{\sqrt{N_{obs}}} = \frac{L_{tot} \mid \sigma(\kappa) - \sigma_{SM} \mid}{\sqrt{L_{tot}[\sigma(\kappa) + \eta_B \sigma_B]}}, \tag{4}$$

where, $N(\kappa)$ is the expected number of events as a function of κ, N_{SM} is the number of events expected from the standard model and N_{obs} is the number of observed events. While, $L_{tot}, \sigma(\kappa), \sigma_{SM}, \eta_B$ and σ_B are the total integrated luminosity, the cross section as a function of κ, the standard model cross section ($\kappa = 1$), the intensity level for background events and the cross section for the background process, respectively.

In Fig. 6 we show the statistical analysis when the experiment does not show any deviation from the SM at 95% C.L. for the λ_{HHH} coupling. These regions correspond to $S < 1.96$ (95% C.L. correspond to $S^2 = \chi^2 < (1.96)^2$) for differents values of the center-of-mass energy, the e^+e^- luminosity and the parameter η_B.

The quantity η_B measure the background importance. As the masses we are considering for the Higgs are different of the Z boson mass then it could be possible separate the Higgs signal from the Z background by reconstructing the jet-jet mass. In this conditions we also take into account the possibility of a small background. In Fig. 6 we show the case with very small background ($\eta_B = 0$) and full background ($\eta_B = 1$).

IV. CONCLUSIONS

As a possible option of the International Linear Collider (ILC), the feasibility of physics opportunities of high energy physics photon-photon interaction has been considered in Ref. [22]. In the high energy photon linear collider, high energy photon beams are generated by inverse Compton scattering between the electron and the laser beams. The $\gamma\gamma$ collider represents a possible opportunity for the triple Higgs boson self-coupling analysis. We have analyzed the triple Higgs boson self-coupling at future $\gamma\gamma$ collider energies with the reactions $\gamma\gamma \to f\bar{f}HH$ where $f = b, t$ and considering the complete set of Feynman diagrams at tree-level and in the frame work of the standard model.

We found that for the process $\gamma\gamma \to t\bar{t}HH$, the complete calculation at tree level gives a production cross-section of the order of a fraction of a femtobarn, i.e., 0.010 fb and 0.007 fb for $M_H = 120, 140\ GeV$, respectively, and at the end of the examined energy range. These values are, however, larger than the production cross-section for $e^+e^- \to b\bar{b}HH$ and $e^+e^- \to t\bar{t}HH$ [23]. The number of events obtained considering the decay products of both t and H is enough to obtain relevant information about the triple Higgs self-coupling. Moreover, this process can be used to probe the $t - \bar{t} - H$ Yukawa coupling.

We have also done a background analysis concluding that the background intensity is below the signal level. The ratio S(signal)/B(background) is show in Fig. 5. On the other hand we have also studied the sensitivity to the values of the parameter κ. We show the results as 95% C.L. regions in the $\kappa - M_H$ plane for different values of the center-of-mass energy $\sqrt{s}$, the luminosity $\mathcal{L}$ and the parameter η_B. These are shown in Fig. 6. The limits for κ are M_H dependent and we can see that the most stringent limit are possible for positive values of κ. Finally, the study of this process is important and could be useful to probe the triple Higgs boson self-couplings λ_{HHH} using a $\gamma\gamma$ collider with very high luminosity and high center-of-mass energy. In addition, to our knowledge, these results have never been reported in the literature before and could be of relevance for the scientific community since the studied process is complementary of other studied in the literature.

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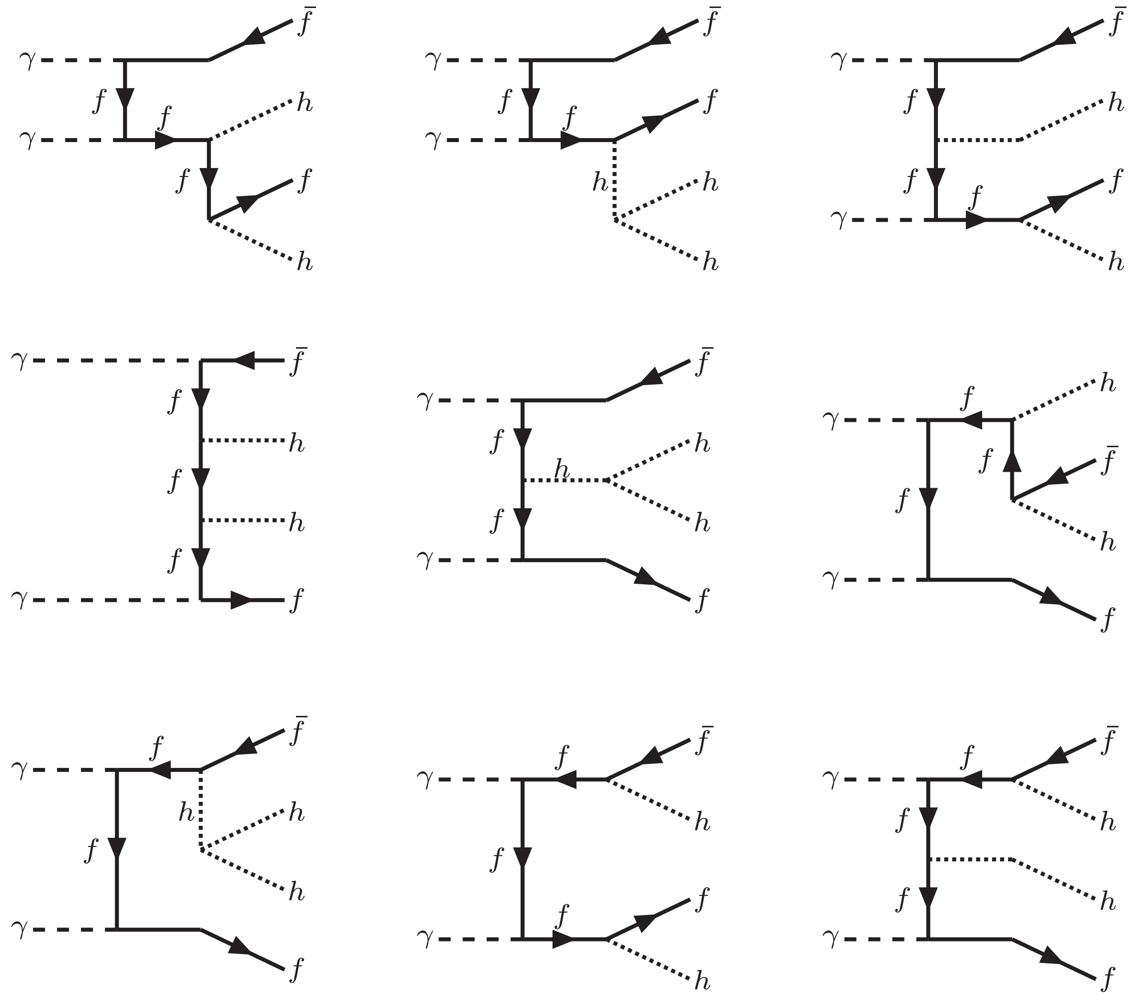

FIG. 1: Feynman diagrams at tree-level (plus fermion inverted circulation) for $\gamma\gamma \to f\bar{f}HH$ with $f = b, t$.

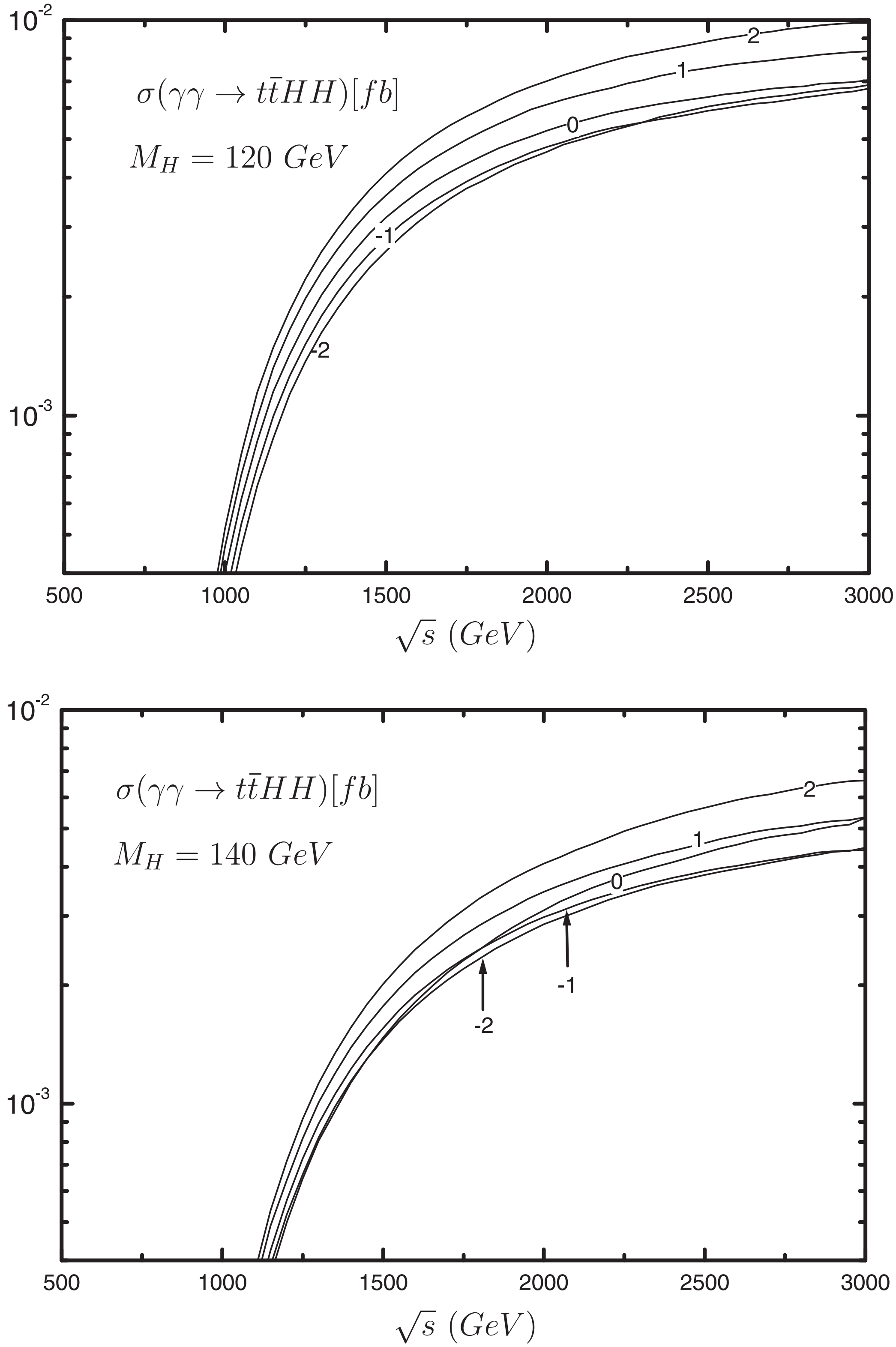

FIG. 2: The dependence of the cross-section with the center-of-mass energy $\sqrt{s}$ for two fixed Higgs masses $M_H = 120, 140\ GeV$. The variation of the cross-section for modified triple couplings $\kappa\lambda_{HHH}$ is indicated by $\kappa = -2, -1, 0, 1, 2$.

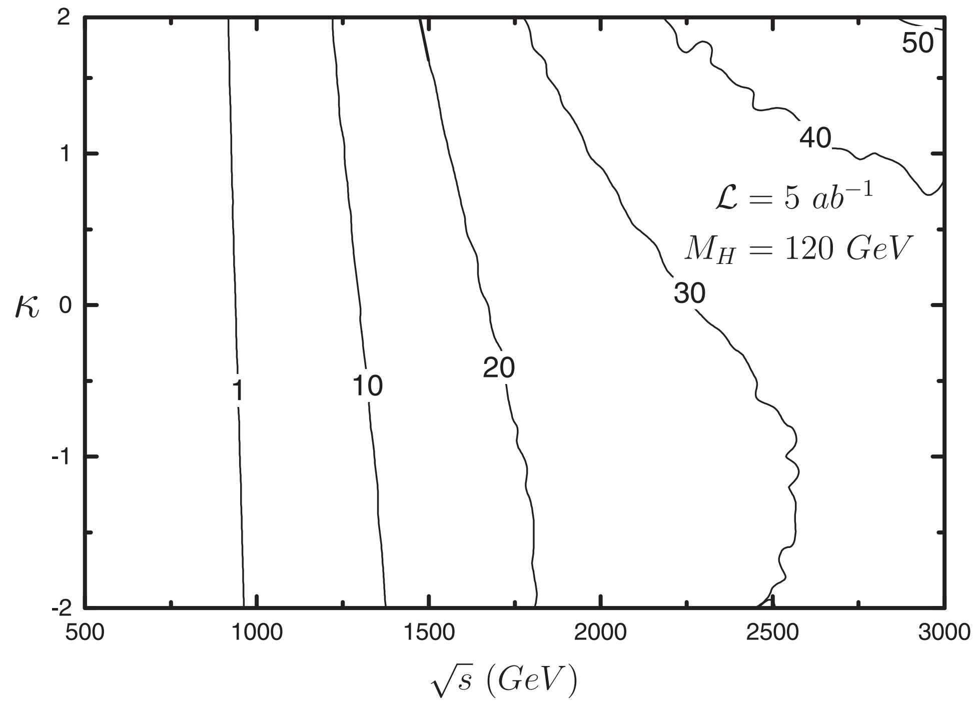

FIG. 3: Contour plot for the number of events of the process $e^+e^- \to t\bar{t}HH$ as a function of $\sqrt{s}$ and κ. The variation of the number of events for modified triple couplings $\kappa\lambda_{HHH}$ is indicated for $\mathcal{L} = 5\ ab^{-1}$ and $M_H = 120\ GeV$.

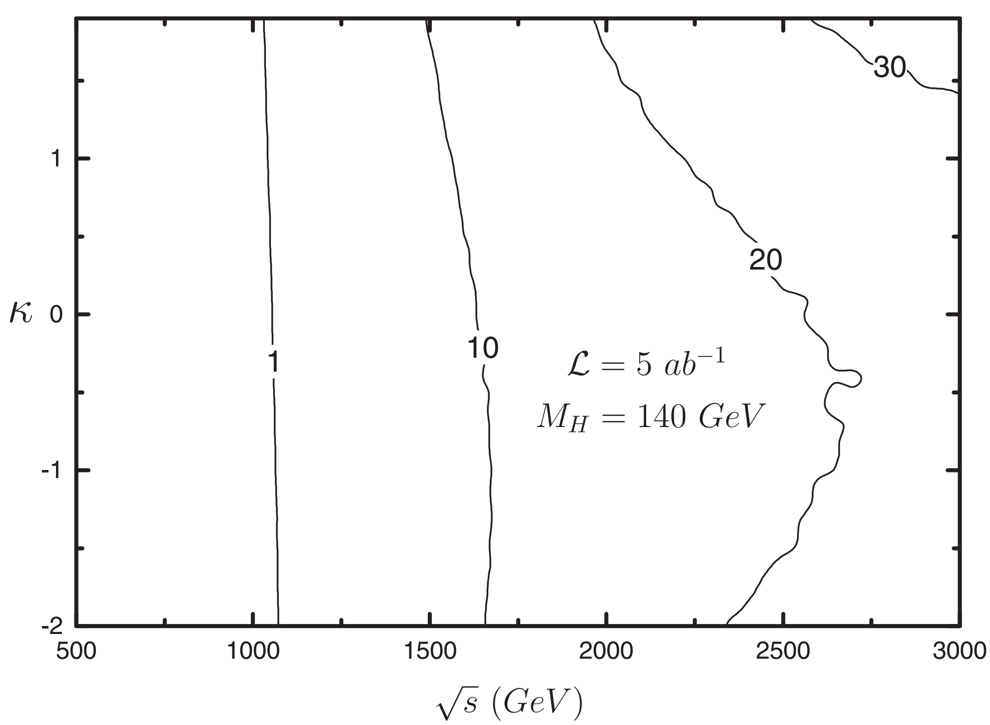

FIG. 4: The same as in Fig. 3 but for $M_H = 140\ GeV$.

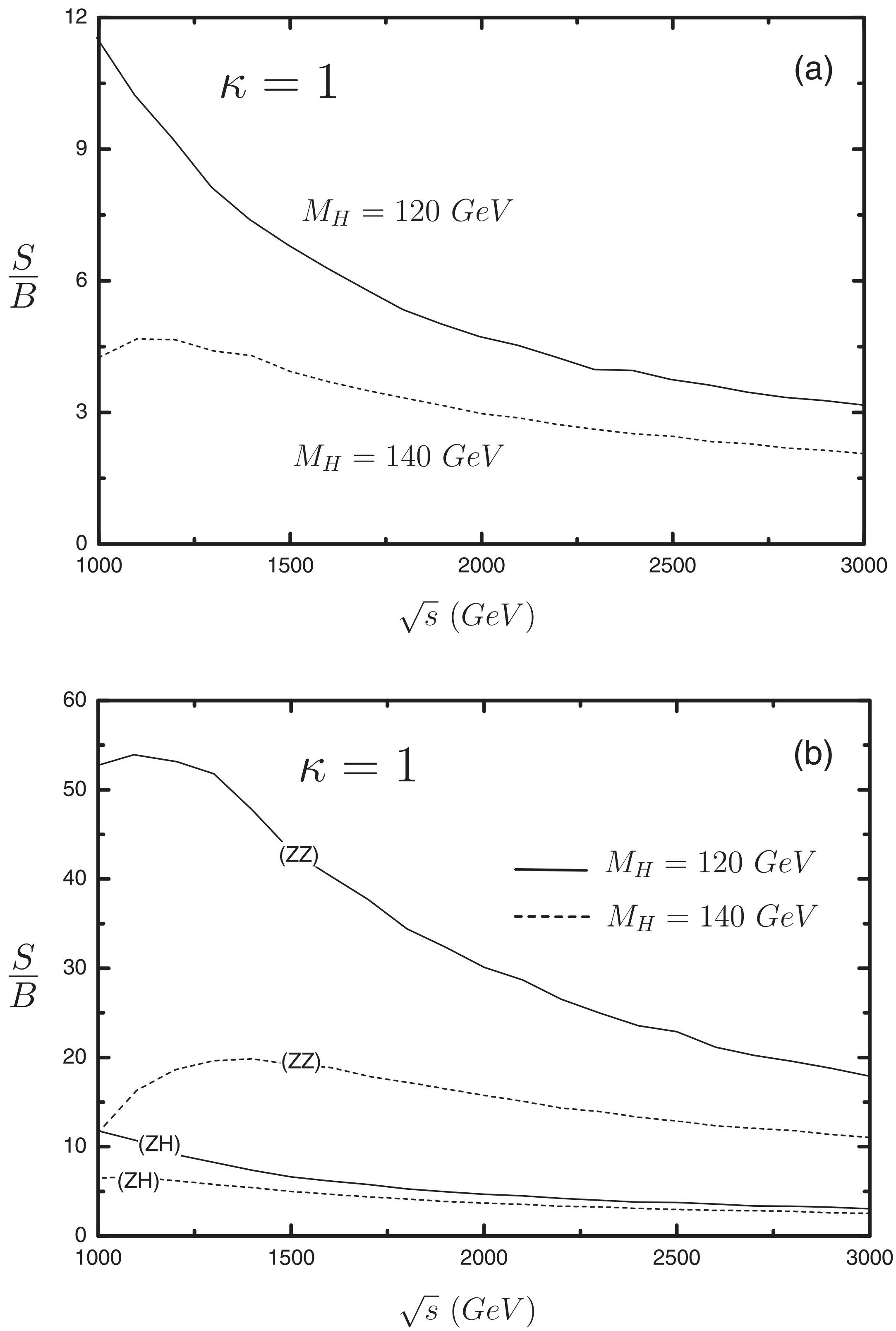

FIG. 5: (a) Ratio S(signal)/B(background) as a function of center-of-mass energy to the process $\gamma\gamma \to t\bar{t}HH$ with $M_H = 120, 140\ GeV$ and $\kappa = 1$. (b) Ratio S/B for the separate contributions of the $t\bar{t}HZ$ and $t\bar{t}ZZ$ backgrounds with $M_H = 120, 140\ GeV$ and $\kappa = 1$.

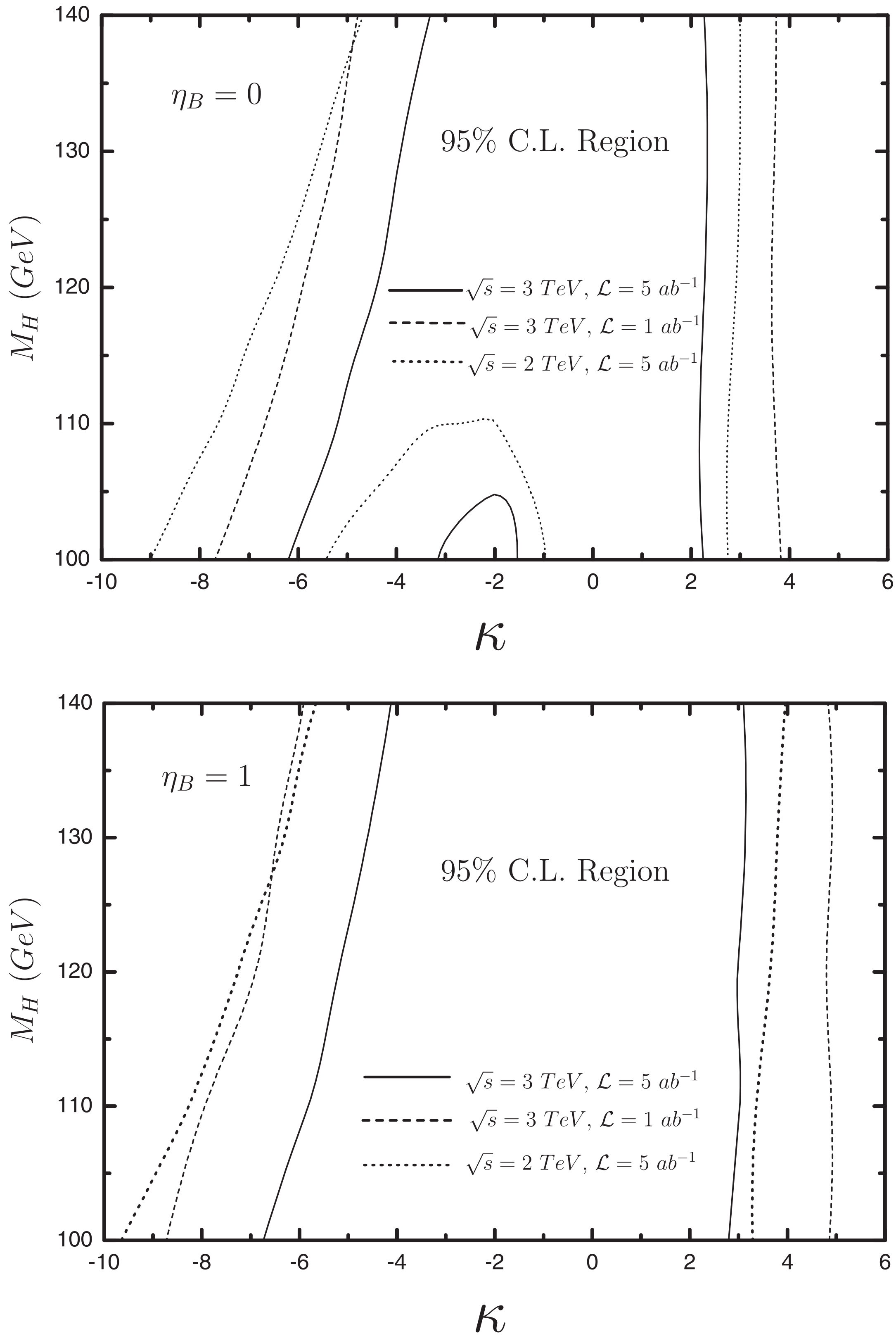

FIG. 6: Region in the $(\kappa - M_H)$ plane where the experiment does not show any deviation from the SM $(\kappa = 1)$ at 95% C.L. for $\sqrt{s} = 2, 3\ TeV$, $\mathcal{L} = 1, 5\ ab^{-1}$ and $\eta_B = 0, 1$.